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SUBSIDENCE MONITORING AND EVALUATION PLAN FOR STRATEGIC PETROLEUM RESERVE STORAGE SITES

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Abstract

Subsidence is occurring at all six Strategic Petroleum Reserve (SPR) sites. It results from a combination of cavern closure, Frasch-process sulphur extraction, fluid withdrawal, and from natural causes. Of these, cavern closure resulting from salt creep is the predominant source. A subsidence monitoring program is recommended that includes: (a) continuation of annual releveling; (b) quadrennial determination of horizontal drift; (c) triennial measurement of gravity values to determine elevation change and to validate releveling data; (d) 1/2400 air photos quadrennially; (e) coordination of other subsidence monitoring efforts, especially involving regional subsidence; (f) continuation of cavern creep modeling; (g) engineering evaluation of observed and predicted subsidence effects; (h) information dissemination in the form of an annual review and report. A priority sequence is suggested that considers observed subsidence and operational factors such as oil inventories and risk appraisal. First (highest) priority is assigned to Weeks Island and West Hackberry. Second (intermediate) priority is given to Bayou Choctaw and Bryan Mound. Third, (lowest) priority is assigned to Sulphur Mines and Big Hill. The priority strategy can be used as a management tool in allocating resources and in determining relative attention that is required at the six sites.

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1.0 INTRODUCTION

The Strategic Petroleum Reserve is a national program involving underground storage of crude oil in large cavities in six separate salt domes in the Texas-Louisiana Gulf Coast area: Bayou Choctaw, LA; Big Hill, TX; Bryan Mound, TX; Sulphur Mines, LA; Weeks Island, LA; West Hackberry, LA. The program involves several existing caverns with volumes up to 33 million barrels, one abandoned 75-million barrel salt mine, and several lo-million barrel cavities that either are or have been leached especially for the program.

Gradual landsurface subsidence and collapse of manmade and natural cavities in salt are an acknowledged fact of life wherever salt or other associated minerals, e.g., sulphur, are extracted (Coates et al. 1981). This subsidence and collapse history provides the impetus to perform cavern stability and subsidence studies to help assess the integrity of crude petroleum storage in the Strategic Petroleum Reserve (SPR), including associated surface facilities over and adjacent to the storage caverns. This interest is not restricted to cataclysmic failures, such as occurred at Allied Chemical's Cavern 7 at Bayou Choctaw in 1954 (SAND80-7140). Other major failures in shafts in salt mines have also occurred; such failures are considered in every salt mining operation, because uncontrollable flooding and loss of the mine can result. Longer term subsidence resulting from creep closure of underground openings may be the greater concern, insofar as surface piping and oil withdrawal systems are affected. Further, perennial flooding resulting from subsidence may become a significant concern at sites near sea level; that is, at Bryan Mound, West Hackberry, and Bayou Choctaw.

The SPR has included cavern creep closure analyses in its long-term performance predictions (Preece and Foley 1984). These analyses predicted volume reduction and associated subsidence, but the estimates were based upon models that contained appreciable uncertainties. The attempts made by the mining companies to monitor subsidence have usually been incomplete and nonuniform, resulting in an inconclusive data base. Further, both the sulphur and salt mining companies have company policies against making their subsidence measurements available. As a result, the current ability to accurately predict subsidence is limited; hence, field measurements are necessary for virtually any subsurface extractive or storage operation.

Subsidence monitoring began at the SPR storage sites in 1982, following in general the plan outlined in the draft long term monitoring plan (SNL 1982). The information obtained from six surveys at five SPR sites between 1982 and 1988 is presented in Goin and Neal (1988). These data have established the magnitude of subsidence ongoing at each site and have shown that more subsidence is occurring at some sites than others.

The subsidence monitoring plan described in this report updates the 1982 SNL draft report. The total effort outlined herein will provide entirely credible predictions of long-term performance and will establish a means for continuous awareness of the effects of subsidence on operations. A strategy is proposed in Section 2.0 for assigning a priority of effort to each site because different attention is required for each set of conditions.

2.0 RATIONALE FOR THE MONITORING EFFORTS

The subsidence history summarized in Appendix B shows that each site has individual conditions and circumstances, and that rates of surface lowering and, consequently, effects on engineered structures, are not equal. For this reason, some sites must receive closer attention than others.

2.1 Engineering Implications

The subsidence measurement and analysis efforts require evaluation and synthesis, and determinations must be made as to their effect on SPR operations. Possible effects include the following (all have been experienced in salt dome operations):

a. Ground failure from subsurface fracturing and/or slumping, e.g., Houston;

b. Anomalous, excessive stress on cavern well strings or surface pipe systems;

c. Breakage of surface structures, e.g., brine pond linings, etc.;

d. Potential cavern collapse, e.g., Bayou Choctaw Cavern 4;

e. Induced fracturing in shafts or drifts sufficient to create water influx (Weeks Island);

f. Subsidence sufficient to produce perennial flooding, e.g., West Hackberry;

g. Surface drainage problems, e.g., Bayou Choctaw;

h. Irregularities or unevenness in subsidence patterns causing anomalous tilt effects on structures.

2.2 Priority Ranking of Sites with Respect to Subsidence Concerns

The following priority ranking of sites is suggested, based on subsidence history, geologic conditions at each site, and perceived risk to storage integrity. The ranking is presented only as a management tool to address the relative importance of subsidence monitoring activities. Its principal use is for planning, budgeting, and the application of resources.

Priority*	Site	Rationale
1	Weeks Island	Failure consequences high
1	West Hackberry	Greatest subsidence rate; flood potential
2	Bayou Choctaw	Cavern 4 collapse potential; flood potential
2	Bryan Mound	Flood potential
3	Sulphur Mines	Site decommissioning
3	Big Hill	Thick and deep caprock; leaching ongoing

*1 = High - Potential <u>major</u> impact on SPR storage objectives.
2 = Medium - Potential <u>significant</u> impact.
3 = Low - Potential small impact.

The rationale for this ordering follows, realizing that this understanding can change in the future with changing conditions, or as more data are accumulated.

Weeks Island: Observed subsidence and lateral drift of shafts are significant over mined-out areas. The consequences of flooding from shaft failure and/or uncontrolled leakage are the most severe of any site, given the large volume of oil in two interconnected chambers.

West Hackberry: Subsidence rates are the largest of any site; the reasons are related to the large amount of cavern volume and rapid salt creep, and possibly to hydrocarbon withdrawal. The continuing enlargement of Black Lake and encroachment on the site in recent years as a result of subsidence emphasizes that continuing concern is required.

Bayou Choctaw: Potential for Cavern 4 collapse is present and would create another BOO-ft-wide lake, similar in dimension to Cavern Lake over collapsed Cavern 7. The effect on operations at this site would be substantial because of this new lake and would require considerable modifications to existing oil storage and drawdown systems.

Brvan Mound: Prior sulphur extraction and attendant subsidence combined with large volumes of oil storage give intermediate ranking to this site. The existence of the largest (35, 20 MMBBL, respectively) caverns in the SPR warrant additional attention.

Sulphur Mines: Continuing gradual subsidence associated with caprock collapse into voids created by Frasch sulphur extraction is expected. Total surface lowering in this century has exceeded 20 ft, the bulk of which occurred during and immediately following the mining (1902-1924). The relatively small volume (25 MMBBL) of stored oil combined with plans for limited tenure of this site give reduced concern for long-term stability. The long-term ownership of the site may necessitate the need for continuing surveillance.

Bin Hill: The lack of sulphur or significant hydrocarbon extraction combined with very thick caprock suggest this site has an extremely low subsidence potential. This site offers a unique opportunity to monitor subsidence throughout cavern leaching, filling, and storage operations.

3.0 RECOMMENDED SUBSIDENCE MONITORING PROGRAM

3.1 Activities

The elements outlined below and discussed in the following sections constitute a program that is sufficient to continuously evaluate the status of subsidence at each site, which in turn will enable the SPR to be alerted to expected events and appraised of their significance to SPR. This should allow time to begin appropriate mitigative measures. In some instances, however, long lead times may be needed.

3.2 Discussion of Plan Elements

A description of each activity listed in Table 1 is presented in the following subsections.

3.2.1. Vertical Point Releveling

Releveling surveys have been conducted about once a year at all five storage sites, and plans exist to do the same at Big Hill. This has been the primary data collection to measure the vertical subsidence at all sites. The surveys should continue, but minor modifications to existing procedures are recommended as follows.

Recommended Modifications to Existing Subsidence Monitoring Network

A review of the subsidence monitoring network was conducted in late 1987 and resulted in the following recommendations (Linn 1987):

1. Control-monument redundancy is needed.
2. **Wellhead** survey points need improved marking and description.
3. Descriptions and markings of other survey points are often obscure and should be made clearer.
4. Redundancy of stations in administrative areas should be reduced.
5. Survey monuments should be physically protected.
6. Photos of survey points should be taken.

Table 1. RECOMMENDED SUBSIDENCE MONITORING ACTIVITIES AND REPETITION INTERVALS

ACTIVITY	BC	BH	BM	SM	WI	WH	Remarks	Discussion (Section)
	REPETITION, YEARS							
A. Field Measurements								
1. Surveying								
a. vertical point releveling	1	1	1	1	1	1	Continuation of 1982-88 effort	3.2.1
*b. horizontal trilateration	4	4	4	4	4	4	Initial emphasis on W. Hackberry, Weeks, and Bayou Choctaw	3.2.2
*2. Gravity observations	3	3(D)	3(D)	3 (D)	3	3	" " " "	3.2.3
*3. Aerial photography, 1/2400 scale	4	4(D)	4(D)	4(D)	4	4	Initial emphasis on flood-prone sites: WH, BC, BM	3.2.4
B. Analysis and Evaluation								
1. Surveillance and evaluation of Gulf Coast regional subsidence	Efforts apply more or less to all sites equally, with variations noted in remark. Continuing effort.							3.2.5
2. Creep closure modeling	"	"	"			"	Sequence of effort follows site priority scheme.	3.2.6
C. Technology Transfer								
1. Engineering application	"	"	"			"	Periodic awareness required	4.1
*2. Annual status update	"	"	"			"	Annual report needed	4.2

*Modification from existing program.
(D): Decision to proceed required, pending results from other sites.
BC = Bayou Choctaw; BH = Big Hill: BM = Bryan Mound; SM = Sulphur Mines; WI = Weeks Island; WH = West Hackberry.

Regarding Recommendation (1), multiple control (reference) monuments are essential to maintain a continuity of measurements over the SPR life cycle. Several monuments have been destroyed or moved, resulting in considerable ambiguity in the data base. Multiple control monuments will also help establish the stability of the reference by way of cross checking. Ideally, each site resurvey should be tied to first-order NGS lines, as better control of average long-term drift is known for those control points.

Regarding Recommendation (2), the precise survey point on the wellheads is frequently difficult to ascertain, sometimes requiring a new surveyor to either guess or sight-in the point. A standard method of marking the survey point would eliminate uncertainty in location.

Regarding Recommendation (3), improved marking and descriptions of survey points on concrete pads and other structures would be helpful to survey crews and would reduce any ambiguities regarding location.

Regarding Recommendation (4), some stations at each site are superfluous and are not providing essential data. They could be eliminated or replaced with other stations, thereby aiding the survey's effectiveness. Additional stations beyond the DOE boundaries would be particularly useful, so that overall trends of individual domes would be available, together with an improved understanding of causes. One result would be to distinguish cavern effects from other domal structures, e.g., spines and shear zones.

Regarding Recommendation (5), physical protection of monuments will assure they are not disturbed by mowers or other equipment. Numerous monuments have been destroyed in only a few years; thus, this step is required for long-term continuity in the subsidence observations.

Regarding Recommendation (6), photos of survey points would be beneficial for documenting the status of survey points, as well as aiding in their description and location. Photos of existing stations were taken in October 1987, and a catalog was given to Boeing Petroleum Services (BPS).

DOE and BPS initiated action in early 1988 to effect needed changes and to reconsider procurement procedures for annual resurveys (Schmedeman 1988).

3.2.2 Horizontal Trilateration

Initial cavern **wellhead** surveys included coordinates, but their accuracy is believed to be third order. The resurveys thus far have not included horizontal coordinates, but creep closure calculations predict that the surface points will drift laterally (Preece 1987). These data are needed to validate code calculations (Segalman 1988); they are probably less significant than the vertical subsidence data and therefore only need be repeated about every three or four years. Horizontal coordinates need not be resurveyed at all points, but should include wellheads, SMS monuments, and a few other points. First-order survey accuracy (qualified) will be required for this purpose, assuming that secondary control monuments are located near the DOE property and away from the influence of salt creep. First-order traverse accuracy requires horizontal closure to surpass one part in 25,000. The motion of points relative to each other within the group of caverns is the required parameter, rather than the absolute coordinate alone, although the latter would also yield the former.

The added cost of obtaining the horizontal control will probably be less than for vertical releveling alone (Stroud 1988). This additional data acquisition should begin at the time of the 1988 resurveys at all sites including Big Hill. The frequency of resurveying may need to be adjusted pending survey results. Because of more rapid salt creep, and their higher priority status, West Hackberry and Weeks Island should receive attention first for these measurements.

The addition of horizontal coordinates is suggested in lieu of more costly tiltmeter installations, such as planned at Weeks Island salt dome. A limited number of tiltmeter observations at the other sites may prove useful, but this has not been demonstrated yet. The initial data from West Hackberry should make this direction clearer, especially if horizontal drift rates are similar to those reported by Deere (1961), at the Fannett, Texas, dome where sulphur was being extracted.

3.2.2 Gravitv Observations

Releveling surveys alone in a number of geologic environments have proven inadequate to provide hypothesis-free rates of vertical crustal movements. This applies to virtually all locations where releveling has been applied, including SPR sites. To reduce inherent ambiguity originating in many sources, **both** repeated gravity observations and relevelings are required (Heck and Malzer 1983). Some authors have proposed replacing leveling by the more economical repeated gravity measurements, but unambiguous estimates of elevation changes are not possible on the basis of gravity data alone (Jachens 1979). Consequently, this replacement is not recommended for SPR, but rather a combination of releveling and gravity.

Changes in elevation (Ah) correspond to changes in gravity (Ag) with $\Delta g/\Delta h$ values of about 3.0 μGal/cm, depending on local conditions. Modern gravimeters used in multiples with repetitive readings can achieve accuracies with standard errors as low as ± 3.0 microgals (Whitcomb and Rundle 1985). It would cost about $25,000 to conduct gravity observations at all six SPR sites (20 stations each), and this cost would be incurred every three years, unless conditions rapidly changed or releveling data were ambiguous. However, the feasibility of using gravity to monitor subsidence at SPR sites needs first to be established; thus, a phased program is indicated.

The initial survey would take somewhat more time, because stations suitable for gravity measurements would need to be selected, described, and photographed. Some stations might coincide with existing releveling monuments; a major effort in establishing observation points is not indicated (Linn 1988). Initial priority should be given to West Hackberry, Weeks Island, and Bayou Choctaw, and decision regarding the other sites might be made pending results of the first resurvey. The resurvey could be made after the first year and then repeated every three years.

3.2.4 Aerial Photography/Remote Sensing

There is no substitute for quality color aerial photography (vertical, stereo) of a site at large scale to provide details of the exact conditions in existence. Color aerial photography is presently being repeated annually for environmental monitoring and documenting the status of surface facilities at each of six storage sites and the SPR St. James terminal. The photography is general purpose and performed at intermediate and small scale, which has varied slightly at each site because of area differences. Thermal infrared imaging and multi-spectral scanning were accomplished for the West Hackberry Cavern 111 oil spill, but they have not been used elsewhere on this project. Color infrared photography has also been used selectively in the past.

Recommended Modification

A more detailed (larger) scale of 1/2400 (vertical, stereo) should be obtained at the time of the next resurvey and then repeated every third or fourth year. Effects of subsidence, including surface fracturing and slumping, may be noted at this larger scale, as has been obtained at Houston (Clanton 1988). Expansion of surface hydrographic features will be particularly helpful to monitor. Initially, priority should be given to flood-prone sites, i.e., West Hackberry, Bayou Choctaw, and Bryan Mound. Weeks Island should also receive priority attention because surface effects over mined areas may appear.

In the event accelerated subsidence or actual collapse occurs, large-scale photography and thermal infrared imagery should made of the locale as an aid in identifying and documenting unstable areas.

Obtaining and interpreting this larger scale coverage should not involve appreciable additional cost if included with the small-scale coverage, and it would provide a valuable complement to the survey data. Additional time for interpreting photos and comparing them with previous years would be the principal resource required.

3.2.5 Surveillance and Evaluation of Gulf Coast Regional Subsidence

Rates of regional subsidence are important to understand, together with measured local subsidence. This is necessary in recognizing that multiple sources of movement are occurring (Appendix A), and that reference monuments are periodically adjusted to absolute values. In most instances, the local subsidence values will not be affected relative to the control reference, but the absolute subsidence is important, for example, where sites are near sea level and flooding is of concern.

Along the southern Louisiana coast, regional subsidence is occurring at a rate of 0.016 ft/yr (5 mm) (Holdahl and Morrison 1974). The Louisiana Geological Survey has continued in recent years to monitor these regional values, together with its DOE-sponsored work on geopressured/geothermal well effects (Trahan 1982). This work is relevant to understanding subsidence effects at the SPR sites and should be monitored.

3.2.6 Creep Closure/Subsidence Calculation Proeram

A continuing analytical effort is currently being conducted at Sandia that parallels the field measurement program described in Sections 3.2.1-5. A graduated sequence is proposed; each site will be addressed with respect to the current level of understanding and relative to the priority ranking in Section 2.2.

West Hackberry and Weeks Island are receiving attention in N 88 with three-dimensional finite element scoping studies that rely on limited parametric data. These studies will in turn lead to more detailed calculations in N 89, using updated material properties and comparisons with empirically derived closure and subsidence data. More quantitative verification of predicted closure rates can be anticipated in the early 1990s.

At the same time the studies at the higher priority sites are maturing, similar studies will be started for Bayou Choctaw and Bryan Mound, or as programmatic direction dictates. A longer term goal is to achieve a predictive capability in about five years that is in quantitative agreement with measured subsidence values.

In addition to the site-specific studies, several collateral efforts are being pursued in parallel. They include resolving discrepancies in salt property data, developing a code to include cavern voids in the finite element mesh, and extending calculations to include fluid extraction and other geometric inhomogeneities.

The analytical efforts described here are leading to capabilities having substantive credibility in predicting long-term performance. Many engineering questions arise having "what if" aspects; this program can help address such questions with expeditious, reliable, and quantitative answers.

3.3 Imnlementation of Subsidence Program

The analysis of 1982-1988 survey data has been done at SNL (Goin and Neal 1988), together with creep closure modeling. A successful program requires coordination and synthesis of all efforts and the transfer of information to operational elements.

Because subsidence is a major programmatic concern, an annual review should be formalized in terms of a process for evaluating the status of each site. More immediate problems should be handled as they occur. The matter of transferring hazard awareness or other pertinent information is presented in Section 4.

Some modifications to this plan may be required as a better understanding of subsidence and of the associated efforts needed to monitor and evaluate them is gained at individual sites. This determination should be a specific discussion point at the annual status review (Sect. 4.2).

4.0 EVALUATION OF RESULTS

Subsidence data and calculations obtained thus far in the SPR program probably have not been fully integrated into long-range planning. This results largely from the lack of data until now, and to a lesser extent from the lack of an identifiable technical focus on subsidence conditions.

4.1 Engineering Annlication

The identification and assessment of subsidence effects on the SPR sites are a major part of the overall program. Actual field experience with potential effects and their impact on SPR development criteria need to be documented and analyzed. Any deleterious conditions can then be addressed at the appropriate SPR level and organization and include such elements as surface facilities, pipelines, casings, shafts, etc.

4.2 Annual Status Update

This activity is a formalized extension of the awareness transfer described above and it will assure proper attention is given to overall subsidence monitoring activities. The primary purpose is to refine/revise predicted subsidence conditions at each site and to provide management with appropriate information required for long-range planning. The principal elements of this annual (approximate frequency) review would include:

1. Data summary of observed subsidence, with emphasis on significant changes, or rates of change.
2. Predicted trends in subsidence and cavern closure, based on cavern shape and volume surveys and three-dimensional model computations.
3. Observed subsidence effects, including surface hydrographic changes, well casing problems, etc.
4. Engineering implications of (1), (2), and (3).
5. Recommended actions concerning (4).
6. Recommended changes to the subsidence monitoring program.

The results of these annual reviews should be documented and published as technical reports.

5.0 CONCLUSIONS AND SUMMARY OF RECOMMENDATIONS

The long-term subsidence monitoring plan presented here is to assure SPR management that appropriate efforts are occurring and will lead to a continuing appraisal of the subsidence status at each site. The program outlined in this plan requires periodic evaluation and updating; some efforts may prove to be of limited use and will need to be modified or discontinued.

The very nature of the subsidence program requires concerted coordination of all monitoring activities, modeling activities, and result analyses. A threefold prioritization of sites for subsidence monitoring purposes is useful in focusing attention according to perceived need:

Prioritv 1.

Subsidence and its associated effects are a maior concern at the Weeks Island and West Hackberry sites because the potential exists for pervasive water incursion and site flooding, respectively.

Prioritv 2.

Subsidence at both Bayou Choctaw and Bryan Mound has significant potential for leading to eventual site flooding and Cavern 4 collapse at Bayou Choctaw.

Prioritv 3.

Subsidence at Sulphur Mines is of lesser concern than at the other sites because of probable phase-out within a few years. Big Hill is also of small concern because the potential for significant future subsidence is low.

Specific programmatic recommendations in this long-term plan include:

1. Minor but important modifications to the existing survey network (Section 3.2.1; Linn 1987, and Schmedeman 1988).
2. Resurvey of horizontal coordinates every third or fourth year, depending on results of the first resurvey (Section 3.2.2).
3. Measurements of gravity values at selected stations every three years (Section 3.2.3).

4. Large-scale (1/2400) aerial photography at all sites every four years (Section 3.2.4).
5. Continued collaboration and awareness of related efforts in measuring regional subsidence (Section 3.2.5).
6. Continued model development of cavern creep closure (Section 3.2.6).
7. Evaluation of above (l-6) data to specific engineering and environmental problems at all sites (Section 3.3).

Specific Management Recommendations Include:

1. Periodic awareness reports to management, indicating significant SPR changes or developments in industry in understanding subsidence effects (Section 4.1).
2. Annual status updates to SPR management that summarize all subsidence monitoring activities, published as technical reports (Section 4.2).

APPENDICES

BACKGROUND INFORMATION

APPENDIX A: CAUSES OF SUBSIDENCE

APPENDIX B: SUBSIDENCE HISTORY AT SPR SITES

APPENDIX A. Causes of Subsidence

Releveling of survey points at SPR sites is concerned primarily with measuring subsidence that is believed to be associated with salt creep and concomitant cavern closure. However, numerous other sources of elevation change are involved, including upward motion of the salt diapir, and these sources need to be recognized in overall perspective. Table A-l summarizes them, estimating values associated with each, where possible. Some movements discussed do not affect the domes, but it is important to acknowledge them because they may affect control monuments located off the domes. Summary explanations follow.

1. Cavern creep: Subsidence values associated with creep closure of SPR caverns average from about 0.03 ft/yr at Bryan Mound to 0.21 ft/yr at West Hackberry, based on releveling of surface survey points. Similar values have been obtained from calculations that employ physical model data (Preece and Stone 1982).

2. Salt diapirism (salt rise and piercement) is ongoing at all sites; the rates of rise can be estimated knowing the ages of displaced strata. Magorian and others (SAND87-7111) estimated the average net uplift of the Weeks Island dome to be on the order of 0.01 in (2.5 mm)/yr, a rate probably higher than average for Gulf Coast domes. Differential rise within individual domes has been seen in mines in the form of spines separated by shear zones (Weeks) and between boreholes (Big Hill, Bayou Choctaw). Rates of rise between spines are thought to vary in time and space.

3. Caprock collapse has occurred at Sulphur Mines and Bryan Mound as a result of sulphur extraction, and at Bayou Choctaw as a result of uncontrolled solution mining, which eroded through the caprock and caused eventual collapse of the overburden. The effects are pervasive: 20 ft and more of surface subsidence at Sulphur Mines (SAND80-7141); 3 ft and more of surface subsidence at Bryan Mound (SAND80-7111); and the collapse of Cavern 7 at Bayou Choctaw in 1954, forming

Table A.l. Sources of Vertical Motion at SPR Sites

Source	Bayou Choctaw	Big Hill	Bryan Mound	Sulphur Mines	Weeks Island	West Hackberry	Remarks
	Site						
1. Cavern creep	X	X	X	X	X	X	(-) 0.03 to 0.21 ft/yr, avg vertical subsidence (at SPR sites)
2. Salt diapirism	X	X	X	X	X	X	(+) Occurring at all sites; avg rate at Weeks Island -0.01 ft/yr
a) spines/shear zones	X	X	N	U/N	X	U	Differential movement evident; may exist in most domes
3. Caprock collapse	(over-burden collapse)	N	X	X	no caprock present	N	(-) Sulphur mining at Sulphur Mines and Bryan Mound the cause; erosion from solution mining the cause at B. Choctaw
4. Regional subsidence	X	X	X	X	X	X	(-) Universal along Gulf coast; 3.3 to 13.1 mm/yr range reflects all three sources and eustasy; the contribution of individual sources is generally <u>uncertain</u>. Growth fault movement probably does not transect domal site
a) sediment compaction and consolidation	U	U	U	U	U	U	
b) geosynclinal downwarping	U	U	U	U	U	U	
c) tectonic/growth fault slippage	U	U	U	U	U	U	
5. Hydrocarbon or ground-water withdrawal	X	X	N	U	X	X	(-) Rates generally uncertain, but but effects evident (off-dome effects)
6. Frost heave, soil expansion, thermal effects	U	X	U	U	U	X	(+) Frost heave probably negligible; soil expansion during wet season uncertain; mima mounds at B. Hill and W. Hackberry
7. Atmospheric loading	X	X	X	X	X	X	(±) **Temporary** elastic deflection during high pressure events (-0.02 ft deflect-ion; greater at higher latitudes)

X = condition present
N = not known to be present
U = unknown or uncertain rate

Cavern Lake (SAND80-7140). The effects of caprock collapse continue at each site, although more slowly than previously. Cavern 4 at Bayou Choctaw has a similar history and geology as Cavern 7, and the potential for collapse exists.

4. Regional subsidence along coastal Louisiana and Texas is reflected in recently published values of relative sea level rise; that is, the values include both increases in tide gauge data and in subsidence inland (Ramsey and Moslow 1987; Penland et al. 1988). Subsidence accounts for a major part of the values overall and includes downwarping of the Gulf Coast geosyncline, compaction, and consolidation of both ancient and recent sediments, growth fault slippage, and subsurface fluid removal. The differential amount attributed to absolute sea level rise (eustasy) has been determined to be about 20% of the total values, which range from 0.011 to 0.043 ft (3.3 to 13.1 mm)/yr.

(4a) Comnactional subsidence is the principal contribution to total regional subsidence, involving Tertiary and Pleistocene sediments, as well as Holocene deposits. Where Holocene deposits are thickest, as in abandoned Mississippi River complexes, compaction may be the primary cause of relative sea level rise. The subsidence attributed to sediment compaction is probably the greater part of the total measured values of Holdahl and Morrison (1974), averaging about 0.013 ft (4 mm)/yr.

(4b) Geosvnclinal downwarping is estimated to have averaged 0.00066 ft (0.2 mm)/yr over the last 60 million years. If this average is anywhere near the downwarping occurring today, the annual contribution to relative sea level rise is a very small percentage. Maximum downwarping has been generally coincident with maximum sedimentation (Kolb and Van Lopik 1958).

(4c) Growth fault slippage has occurred regularly during geologic time and may be occurring today, but no current estimate exists for this component of activity. Penland et al. (1988) believe this factor contributes a very small amount to relative sea level rise. Growth fault slippage is the likely source of microseismic activity at the Parcpurdue geopressured-geothermal well prospect, 25 miles northwest of Weeks Island (Van Sickle et al. 1988).

5. Fluid withdrawal, either groundwater or hydrocarbon, affects local areas, e.g., Houston, Baton Rouge, and New Orleans (Holzer 1984). However, subsidence due to natural causes is much more significant overall than that caused by fluid withdrawal, even though local amounts may be several feet. Some SPR sites are probably affected by hydrocarbon extraction, although the amount at each site is uncertain. Bryan Mound appears unaffected in this regard, because it has not been a producer. West Hackberry appears to have had major subsidence beneath Black Lake associated with the production of some 135 MMBBL of oil. Bayou Choctaw, Sulphur Mines, and Weeks Island have probably experienced subsidence resulting from hydrocarbon extraction, but the amounts are uncertain. The subsidence caused by subsurface fluid extraction does not affect areas overlying the salt, but adjacent areas may be affected, including many control monuments.

6. Frost heave serves to uplift shallow survey monuments if they are not planted well below the zone of frost penetration. The possible effect on SPR survey points is unknown, but is probably negligible, because soil freezing seldom occurs in coastal Louisiana and Texas. Soil expansion during heavy or extended rainfall is likely, but the amount occurring is unknown. Mima mounds, also called prairie or pimple mounds, which are some fifty feet across and up to several feet high, exist at West Hackberry and Big Hill but are of uncertain origin. They may be soil development structures.

7. Atmospheric loading can produce short-term deflections of the crust, with peak-to-peak vertical displacements of 0.05-0.07 ft (15-20 mm) (Van Dam and Wahr 1987). These effects are systematically larger at higher latitudes because of larger variations in pressure. Based on data from lower latitudes, estimates are that the displacements are probably <0.03 feet along the Gulf Coast. It is important to recognize these deflections in concert with other data, because they are similar in magnitude to values attributed to annual subsidence caused by creep closure and are large enough to affect significantly some point positioning measurements. To accurately assess displacement, pressure data from a 1000-km radius around a point are required.

APPENDIX B.

Subsidence Historv at SPR Sites (Summarv of Goin and Neal 1988)

APPENDIX B.l.

Bavou Choctaw Salt Dome

Allied Chemical's Cavern 7 collapsed in 1954, creating Cavern Lake on the north side of the dome. This failure resulted primarily from collapse of the overburden over the caprock, because intensive and uncontrolled brining had induced solutioning and erosion into the caprock above the salt.

Conditions similar to those that led to the failure of Cavern 7 exist at Cavern 4. Erosion into the caprock extends some 30 feet above the salt contact. Even though no oil is stored in Cavern 4, a collapse would endanger and/or damage other caverns and withdrawal systems, because a predicted 800-ft diameter collapse feature and lake would ensue. Some 3 ft of surface subsidence is believed to have occurred prior to 1980 along an access road to the cavern; some of it may be related to brine pond loading. Clearly, surveillance of this cavern is indicated, and in fact, a collapse warning system was installed in 1984 to provide immediate information about sudden changes in elevation (Todd and Smith 1987).

Approximately annual SPR surveys show that the lowest average subsidence rates are adjacent to Cavern Lake near the north boundary of the site, averaging about -0.05 ft (15.2 mm) per year. The highest rates appear near the southern site boundary over Cavern 19 and average about -0.11 ft/yr (33.5 mm), about twice that along the northern boundary. The values around the office and shop buildings, pump station, and brine pond are intermediate between the north and south extremes, averaging about -0.075 ft/yr (21.3 mm). There was no indication that Cavern 4 was subsiding at a faster rate; in fact, the value was slightly less than the site average (-0.06 ft/yr).

This dome has produced about 30 MMBBL of oil, a large volume, albeit not as much as many domes, but probably sufficient to produce minor subsidence. The large volume of pre-existing caverns and newly created SPR caverns equal more than 100 MMBBL and is sufficient to warrant detailed attention to monitoring subsidence.

The generally low elevation at this site creates a hazard during flood periods; additional subsidence will only intensify the flood hazard.

APPENDIX B.2.

Big Hill Salt Dome

The subsidence environment at this dome is expected to be the least problematic of any of the six domes used for the SPR. Sulphur has not been extracted here, and the relatively small oil production is largely away from the dome. Two existing caverns for LPG storage have a combined volume of less than a million barrels and are north of the SPR area. Surface elevations of SPR cavern wellheads are well above the 100-year flood levels.

In addition to these positive attributes, the caprock is one of the thickest on the Gulf Coast, averaging some 1,360 ft over the 14 SPR caverns.

Baseline elevation data from existing survey monuments were obtained prior to the start of cavern leaching on October 1, 1987. This is the first site at which such data were obtained before beginning activities that were potentially subsidence producing. As a result, fewer ambiguities in data interpretation may be anticipated.

APPENDIX B.3

Bryan Mound Salt Dome

Sulphur mining from the caprock overlying Bryan Mound produced some 5 million tons from more than 2000 wells between 1912 and 1935. How much total subsidence has occurred is uncertain because accurate records are not available, but at least 3 to 5 feet is known to have occurred, based on a comparison of modern and historical topographic maps (SAND80-7111). Wherever Frasch-process sulphur extraction has been used, subsidence has occurred in varying amounts, largely because mining is relatively uncontrolled. In some cases, more subsidence has occurred than can be accounted for with the volume of extracted sulphur; this results from limestone dissolution and water removal. The very fact that Frasch mining has occurred is sufficient reason to monitor subsidence, as adverse effects are widespread and common (Coates et al. 1981).

The presence of the largest and second largest caverns (35+ and 20+ MMBBL) within SPR suggests continuing surveillance is necessary, even though unusual creep occurrence has not been noted. In laboratory creep tests on this salt, the material crept slower than any other salt known to the investigators (Wawersik and Zeuch 1984). The average subsidence over a 57-month period was -0.029 ft/yr (8.8 mm), which is the lowest rate of any of the five sites that presently have active cavern storage. Because of uncertainty in adjusting the data, conclusions are tenuous. A slight trend toward increasing subsidence in the interior caverns (1, 4, 104, 107, 110) may exist. Although measured surface subsidence is small and the site appears stable, the large volumes of stored oil dictate continued close investigation. The possibility of accelerated subsidence in some areas cannot be ruled out because observations are available for only a few years.

Flood protection at this site is of less concern than at West Hackberry, but cumulative subsidence may require dike enhancement in the future.

APPENDIX B.4.
Sulphur Mines Salt Dome

Some open pit sulphur extraction began in the late 19th century, and large-scale sulphur mining was conducted from 1902 to 1924, with some 9.4 million tons removed. The Sulphur Mines dome was the location of Herman Frasch's pioneering work on perfecting the steam extraction process that is named after him. Before the sulphur extraction, the dome had a relief expression of more than 20 ft. Following the commencement of mining, caprock collapse began, and fill was added in numerous locations where surface subsidence occurred. Enough fill was added that almost none of the original soil is left exposed at the surface. It is known that some 20 ft of subsidence has occurred and is continuing at a rate of about an inch per year. This surface subsidence is continuing even though sulphur has not been mined in nearly 65 years; gradual settlement and readjustment of underlying caprock is probably still occurring (SAND80-7141).

The SPR caverns are located on the dome, whereas the support facilities are all off the dome. Subsidence over the caverns (on the dome) averages about -0.10 ft (30.5 mm) per year, whereas the support facilities and associated survey points average about -0.04 ft (12.2 mm) per year. This subsidence on the dome is evidently the result of cavern closure and possibly residual collapse of caprock that has been occurring continuously ever since sulphur mining stopped in 1924.

There are no conspicuous patterns associated with the subsidence other than the southernmost survey points (most distant from the dome) have subsided the least. Also, the SMS monuments (away from wellheads and other structures) appear to have subsided less than adjacent points; this possibly can be attributed to soil compaction beneath engineered facilities.

Plans for limited future use, combined with a small storage capacity, tend to reduce attention to this site. Continuing subsidence monitoring is necessary in view of the above history and because of long-term responsibility for cavern integrity; that is unless ownership is transferred following oil withdrawal at a future date.

APPENDIX B.5.

Weeks Island Salt Dome

Subsidence at this site has its origin in creep closure of mined underground openings that are equivalent in volume to some 100 MMBBL, and in the production off dome of some 230 MMBBL of oil, more oil than at all of the other five domes used for SPR storage.

Releveling of Weeks 2 monument in 1987, which was established in 1931, indicates that more than 5 ft of subsidence has occurred. Measurements of other surface monuments that began in 1983 show subsidence values up to about -0.2 ft/yr, with the largest elevation losses occurring inside the surface projection of the mine boundaries.

The 50-month duration of SPR releveling shows a reasonably consistent pattern of subsidence. The most surface subsidence, -0.91 ft, was observed at Weeks 2, which is located within the boundaries of both underground oil storage levels. The least subsidence (-0.06 ft) was observed at monument SMS 3, outside the oil storage boundaries. Near the mine boundaries, intermediate values of -0.25, -0.21, and -0.18 ft were observed at the production and service shafts, and the fill holes, respectively. Monument SMS 1 showed total subsidence of -0.47 ft; it is immediately outside the upper storage level boundary (projected), but well within the lower level boundary (projected).

The consequences of subsidence at this site may be more pervasive in comparison with the other SPR sites in that 73 MMBBL of oil are contained in two interconnected chambers (former Morton Salt Co. mine). The potential for flooding resulting from leaks induced by creep and fracturing is a significant threat, especially flooding associated with shaft failure. Consequently, continuing surveillance is needed.

APPENDIX B.6.

West Hackberrv Salt Dome

Black Lake, on the north edge of the SPR site expanded from 4 to more than 25 square miles during the period 1955-1980 **(SAND80-7131)**. An estimated 3 to 5 ft of subsidence occurred between 1933 and 1978 to produce this expansion, probably as a result of intensive hydrocarbon and groundwater withdrawal that began about 1930. Local declines in groundwater levels may also contribute to subsidence; an approximate 41 ft-decline in head occurred between 1952 and 1970 at Hackberry Village. This is an area of minimal sand for onshore Gulf Coast sediments, and, of probable greater mud compaction.

Releveling of subsidence monuments at the SPR site over a 5-year period indicate a broad depression decreasing to the south and east, which is generally coincident, although centered slightly northwest, to the distribution of caverns Maximum subsidence during this period was -1.43 ft, the most rapid rate of any site. Average rates are about -0.21 ft/yr (64 mm), a significant amount.

The total volume represented by the subsidence depression approaches 3 MMBBL, an amount approximating volume loss resulting from predicted cavern creep closure, including the abandoned Olin Corporation caverns.

The projected maximum subsidence is some 8.5 ft in 30 years. Without mitigative measures, substantial local flooding will occur. The area of local marshes and Black Lake will likely continue to expand, with the continued production of oil and gas, and associated groundwater withdrawal. The subsidence of some 5 ft and the associated increase in the area of Black Lake began in about 1933, concurrent with hydrocarbon extraction, and, both have been increasing since that time. Thus, a combination of factors is probably contributing to this local subsidence pattern.

Because of the generally low elevation and proximity to coastal flood surges associated with hurricanes, the potential flood hazard at this site is of concern. Because the abandoned Olin Caverns underlie the brine and raw water holding ponds, the possibility of cavern collapse was considered in SAND80-7131. As a result of these conditions, the need to be aware of subsidence is high.

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